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# Glueball enhancement by color de-confinement

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## Abstract

High energy heavy ion collisions lead to the formation of a strong coupling de-confined phase in which the lightest glueballs are numerous and stable. We analyze how their properties manifest themselves in experimental spectra and show that they provide a good signature for color de-confinement.

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# 1 Introduction

Quantum Chromodynamics (QCD) is the theory of the strong interactions [1]. At low temperatures its elementary constituents are mesons, baryons and glueballs [2], this is the hadronic phase where all states are color singlets. At very high temperatures one expects a phase transition, called de-confinement, to take place. The new phase was thought to be a plasma of quarks and gluons and was named the Quark Gluon Plasma (QGP)[3]. However, a formulation of the dynamics in the region above the transition temperature  $T_C$ , based on a description of recent experiments in ultra relativistic heavy ion collisions [4], states that, despite de-confinement, the color Coulomb interaction between the constituents is strong and a large number of binary (even color) bound states, with a specific mass pattern, are formed [5]. This phase I call Strong Coulomb Phase (SCP). The QGP phase occurs at a much higher temperature  $T_{QGP} > (2 - 3)T_C$ .

My aim is to study the behavior of QCD in the transition from the SCP to the hadronic phase centering my attention in the behavior of the scalar glueballs. I am not the first to propose the glueballs to characterize de-confinement [6] but I single out in here a different dynamical picture. Glueballs are bound states of gluons, the gauge bosons of QCD. This unique structure led to an intense experimental search, since they were first theoretically contemplated [2], which has not produced a clear picture of their spectrum. Moreover, they are expected to be broad because they mix strongly with quark states. The lightest glueball is a  $0^{++}$ , which I shall label by  $g$ .

Recently, I have proposed an interpretation of the scalar particles that contemplates a rich low lying glueball spectrum [7]. The analysis has been modelled by  $\frac{1}{N_C}$  physics on which I have also based my estimates. I was led to a dynamical scenario where the OZI rule is broken and a low mass glueball,  $g$ , arises from the mixing of a pure OZI conserving glueball and a  $\sigma$ -meson, which are almost degenerate in mass. In this scenario  $g$  is narrow although it remains hidden in the tale of the  $\sigma$ -meson. Experimentally they appear as a unique and broad resonance, the  $f_0(600)$  [7].

My purpose is to show that these two states,  $g$  and  $\sigma$ , behave in a very characteristic way across the de-confinement transition and therefore lead to observable effects associated with the SCP phase transition.

## 2 Behavior of the $g$ with temperature

The realization of scale symmetry in Gluodynamics (GD), the theory with gluons and no quarks, provides a relation between the parameters of the lightest scalar glueball, hereafter called  $g$ , and the gluon condensate [8, 9, 10],

$$m_g^2 f_g^2 = -4 < 0 | \frac{\beta(\alpha_s)}{4\alpha_s} G^2 | 0 >, \quad (1)$$

where  $f_g = \langle 0 | g | 0 \rangle$ ,  $m_g$  the  $g$  mass, and the right hand side arises from the scale anomaly. GD provides a description for glueballs which almost coincides with that of QCD in the limit when the OZI rule is exactly obeyed, i.e., when decays into quarks which require gluons are strictly forbidden [7].

Lattice results [11, 12] and model calculations [13, 14, 15] support the traditional scenario [16, 17], that the condensate is basically constant up to the phase transition temperature  $T_C$  ( $150 \text{ MeV} < T_C < 300 \text{ MeV}$ ) and decreases slowly thereafter until it dilutes (or evaporates) into gluons at  $(2 - 3)T_C$ . In this regime the mass of  $g$  changes slowly across the phase transition [13, 14, 15] and might even increase beyond  $T_C$  as the gluon binding energy decreases [5] (see Fig. 1). These results and Eq.(1) determine that  $f_g$  will be small only close to the dilution temperature when, in GD, scale invariance is restored. However, around  $T_C$ ,  $f_g$  is sizeable and therefore we are able to use in the scalar sector the OZI approximation of QCD, where glueballs and mesons are almost decoupled, and therefore the scalar glueballs of QCD behave similarly to those of GD [7].

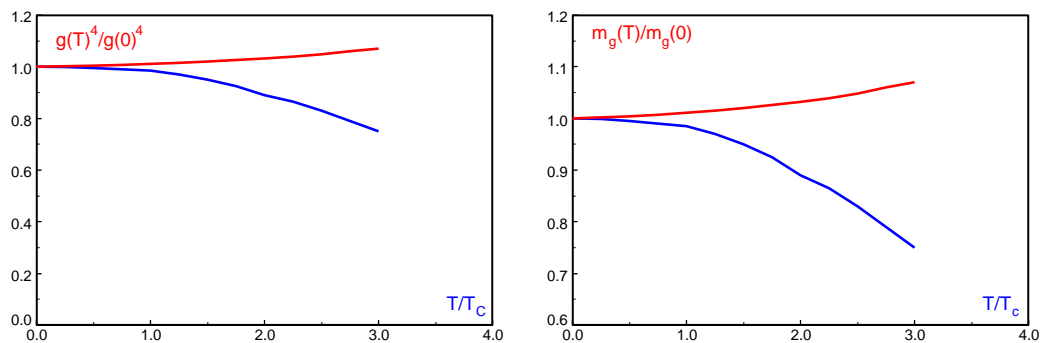


Figure 1: Behavior of the gluon condensate,  $g^4 = m_g^2 f_g^2$ , and the mass,  $m_g$ , of  $g$  across the de-confinement phase transition for various calculations mentioned in the text. The allowed values for different model calculations occur between the two lines.

I assume for the discussion a recent formulation of the dynamics in the region above  $T_C$ , which states that despite de-confinement the color Coulomb interaction between the constituents is strong and a large number of binary (even color) bound states, with a specific mass pattern, are formed [5]. With

this input, the scenario I envisage for GD goes as follows[18]. The strong Coulomb phase is crowded with gluon bound states and  $g$  is the lightest. As one moves towards the dilution limit, the binding energy of these states decreases, the gluon mass increases, and therefore the color and singlet bound states increase their mass softly until the gluons are liberated forming a liquid [5, 19, 20]. However, as one cools towards the confining phase, color and singlet states decay into the conventional low lying glueballs, in particular  $g$ . Thus the number of  $g$ 's becomes large.

Moreover, going to QCD, one realizes that above the phase transition the multiplicity of glueball channels is larger than below. The ratio of glueball to meson channels goes from 1 to 8 below the phase transition to 1 to 2 above [5].

Thus our first result is that the number of scalar glueballs is much larger in SCP than in the cold world.

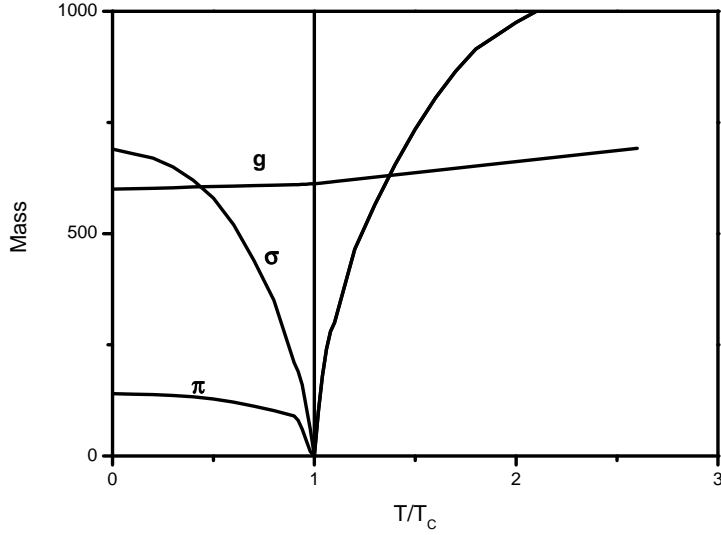


Figure 2: Behavior of the masses of  $\sigma, \pi$  and  $g$  across the QGP phase transition according to model calculations.

The physical  $g$  and  $\sigma$  arise from the degenerate ones via mixing,

$$g = g_0 \cos(\theta/2) - \sigma_0 \sin(\theta/2), \quad (2)$$

$$\sigma = g_0 \sin(\theta/2) + \sigma_0 \cos(\theta/2), \quad (3)$$

where, the physical fields are expressed in terms of the degenerate OZI fields,  $g_0$  and  $\sigma_0$ , and the mixing angle  $\theta$ .

The  $\sigma$  meson decays into two pions or two photons [7],

$$\Gamma_{\sigma \rightarrow 2\pi} \sim 1.5 \cos^2(\theta/2) \left( \frac{m_\sigma(\text{GeV})}{1\text{GeV}} \right)^3 \text{ GeV}, \quad (4)$$

$$\Gamma_{\sigma \rightarrow 2\gamma} \sim 10.5 \cos^2(\theta/2) \left( \frac{m_\sigma(\text{GeV})}{1\text{GeV}} \right)^3 \text{ eV}. \quad (5)$$

Therefore the physical scalar glueball  $g$  decays, due to its  $\sigma$  component, decays also into two pions or two photons [7],

$$\Gamma_{g \rightarrow 2\pi} \sim 1.5 \sin^2(\theta/2) \left( \frac{m_g(\text{GeV})}{1\text{GeV}} \right)^3 \text{ GeV}, \quad (6)$$

$$\Gamma_{g \rightarrow 2\gamma} \sim 10.5 \sin^2(\theta/2) \left( \frac{m_g(\text{GeV})}{1\text{GeV}} \right)^3 \text{ eV}, \quad (7)$$

If we assume that the  $\sigma$  is the  $O(4)$  partner of the  $\pi$  in the chiral symmetry realization of QCD, its mass decreases when approaching the phase transition, becoming degenerate with the pion at  $T_C$  (see Fig.2). Beyond  $T_C$ , in the SCP, chiral symmetry is restored, and  $\pi$  and  $\sigma$  remain degenerate for  $T > T_C$ . Thus in the SCP the  $\sigma$  can only decay in  $2\gamma$  for obvious kinematical reasons. The glueball  $g$  does not vary its mass in this region appreciably. Thus even before we reach  $T_C$ , the mixing between  $g$  and  $\sigma$  disappears (see Fig.2) and  $g$  becomes stable around  $T_C$ . However, in the SCP the mass of the  $\sigma$  increases and in a certain region of  $T$  it again becomes degenerate with  $g$  and mixing is restored. Thus the physical  $g$  is able to decay, once the  $\sigma$  component is attained, to  $2\gamma$ .

Summarizing, in the SCP the ratio of the scalar glueballs to mesons increases and both the  $g$  and the  $\sigma$  can only decay to  $2\gamma$ .

### 3 The cooling of the fireball

When two heavy ions collide at ultra-relativistic energies, if the collision is quite central, a hot region of space time is produced called the fireball [4]. Let me incorporate in the cooling of the fireball the dynamics of QCD as described above [18]. My starting point is SCP with a temperature  $T_C < T < 3T_C$ . This plasma is almost a perfect fluid of hadronic matter with low viscosity and full of binary states [5]. The lowest mass  $q\bar{q}$  states are the pseudoscalar pion  $\pi$  and the scalar meson  $\sigma$ , which are here bound states of the strong color interaction. The lightest glueball state is  $g$ . The behavior of  $g$  runs together with all other hadronic processes leading to a collective flow but, in the OZI approximation,

it can be singled out. Let me consider how the cooling of this plasma affects the population of glueballs and their general flow.

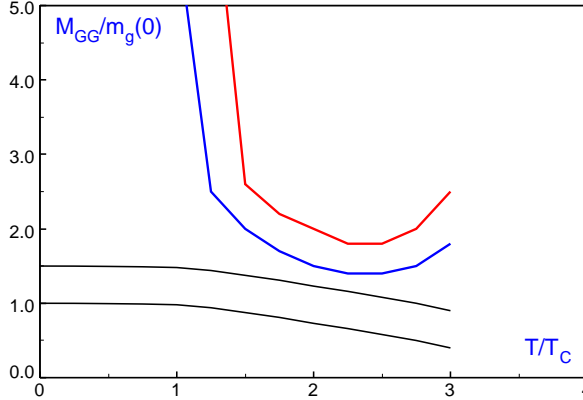


Figure 3: Behavior of the glueball masses as one approaches the de-confinement phase transition. The mass of the color singlet states remains basically constant while the mass of the color states increases dramatically.

As the fireball cools a “large number” of gluonic bound states decay by gluon emission into  $g$ ’s. The emitted gluons form new bound states of lower mass due to the strong color Coulomb interaction. As we approach the confinement region the mass of the color bound states increases and it pays off to make multiparticle color singlet states, which decay by rearrangement into ordinary color singlet states (see Fig.3). Since the coupling is strong and the phase space is large, these processes take place rapidly. Thus in no time, close to the phase transition temperature  $T_C$ , a large number of scalar glueballs populate the hadronic liquid. In our idealized OZI world they interact among themselves and with quark matter only by multi gluon exchanges, i.e., weak long range color Van der Waals forces. These forces allow the glueballs to be dragged by the hadronic liquid with the flow determined by the kinetics of the binary states from which they all proceed [5].

## 4 Experimental signatures

I have presented all the ingredients necessary to discuss the observational signatures. I foresee two types of signatures:  $2\gamma$  decays and  $2\pi$  decays.

It is clear that the  $\sigma$  and the  $g$  will decay in the SCP only to  $2\gamma$ . The width of the  $\sigma$  will be strongly temperature dependent, due to the temperature de-

pendence of its mass. On the contrary the  $g$  will only decay in the temperature range where mixing takes place, i.e. when their masses are close (see Fig.2). Besides their mass variation both widths will be broadened by the energy of the heat bath. Thus we expect a broad  $\sigma$  meson, whose width is temperature dependent, and a narrow  $g$  whose width is temperature independent but has a temperature threshold. The enhancement in the  $g$  with respect to the hadronic phase arises because of the larger population in the SCP as described above, since the ratio of glueball channels to meson channels changes from 1:8 to 1:2, and because these particles are stable in the medium against the dominating hadronic decays. The PHOS detector at LHC, whose capability of detecting  $\pi_0$  is impressive [21] should be able to detect both the  $\sigma$  and the  $g$  (see Fig.4)<sup>1</sup>.

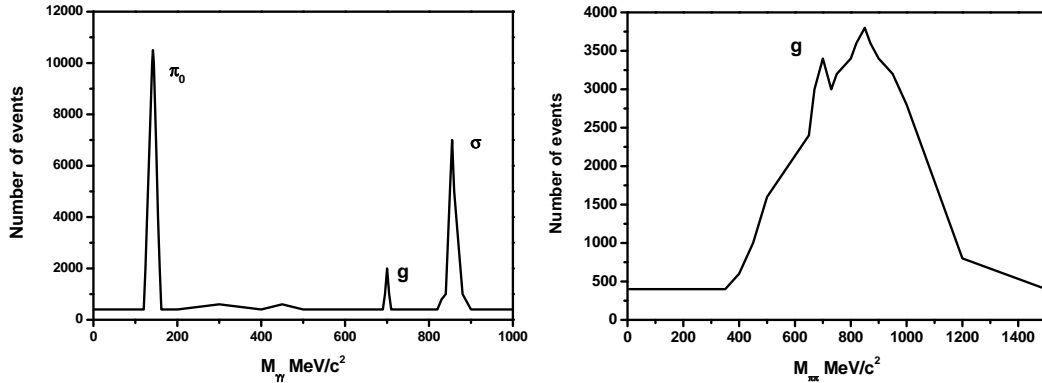


Figure 4: Expected fit to the two-photon invariant mass spectrum and the two-pion invariant mass spectrum in central Pb-Pb collisions after subtraction from the background. The  $2\gamma$  decays should allow for a clear separation of  $g$  and  $\sigma$ . The  $2\pi$  decays will show the  $g$  arising above the  $\sigma$  background.

Let me now look into  $2\pi$  decays.  $\sigma$  and  $g$  are stable against these type of decays until  $m_\sigma$  becomes greater than  $2m_\pi$  for the former, and mixing takes place for the latter. Thus they cross the phase transition temperature,  $T_C$ , as stable states (see Fig.2). This mechanism provides us with a “time delay” associated with the cooling after the phase transition. Thereafter the typical mechanisms for their hadronic decays take place. Thus, if we were able to measure a  $2\pi$  invariant mass plot, tagging for this time delay, an enhanced signal would be observed. If one does not tag, the delay will appear as a narrowing of the width. One further effect which enhances the signal is the

<sup>1</sup>I expect that the broadening of the  $\pi_0$  width is not only due to the heat bath but also to the temperature dependence of the pion mass

increase in the number of events due to the larger population of glueballs in the SCP. Thus the count rate for the particles will increase and the width of its peaks will narrow. I expect, therefore, that  $g$  will come out from the  $\sigma$  background (see Fig. 4).

Let me conclude by stating that I have analyzed the behavior of a peculiar hadronic state, the scalar glueball,  $g$ , in a hot hadronic medium. This state, according to a recent description [7] appears in nature mixed with a scalar meson,  $\sigma$ . I have discussed in physical terms how these particles, which are created copiously in the strong color Coulomb phase, behave as the fireball cools down. We have seen that the weak coupling of  $g$  with other hadronic states and the chiral properties of the  $\sigma$  provide them with a well defined behavior in the plasma as the temperature drops. This behavior is transferred to its detectable decay products leading to a peculiar emission of photons and pions which hints a possible signature for SCP formation. Finally the large production of the  $g$  in the medium allows for enhanced counting rates compared with the zero temperature scenario.

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